Energy-Aware Optimization of Zero-Energy Device Networks

Nikos A. Mitsiou, *Student Member, IEEE*, Vasilis K. Papanikolaou, *Graduate Student Member, IEEE*, Panagiotis D. Diamantoulakis, *Senior Member, IEEE*, and George K. Karagiannidis, *Fellow, IEEE*

***Abstract*— In this work, the optimal resource allocation for a zero-energy device network with quality of service requirements is investigated, aiming to minimize the average energy consumption. Under these considerations and accounting for the circuit power consumption of the devices' hardware, the employment of slotted ALOHA for the uplink data transmission is examined. The derived non-convex optimization problem is transformed into an equivalent convex problem in order to be optimally solved in polynomial time. The solutions of the optimization problem are then given in closed form. Finally, simulation results demonstrate the optimal resource allocation strategy of the zero-energy device network. Notably, taking into account the circuit power consumption leads to a more energy efficient resource allocation scheme.**

***Index Terms*— Slotted ALOHA, resource allocation, wireless power transfer, energy harvesting, zero-energy devices.**

I. Introduction

According to Koomey's law [1], the number of computations per Joule of energy is increasing every year, leading to a decreased energy demand by the connected devices' electronics. As a consequence, wireless power transfer (WPT), which enables energy harvesting from radio frequency signals, emerges as a feasible alternative to the fixed energy supply of low powered devices. WPT is an efficient approach to charge a wireless powered device (WPD) in a controlled, predictable manner, but can also yield environmental benefits. A comprehensive survey on WPT can be found in [2]. WPT is of paramount importance for the next-generation Internet-of-Things (IoT), since it is the main enabler of zero-energy devices (ZEDs) [3]. The latter are a special case of WPDs that, from the end-user perspective, operate without a battery, which practically means that a ZED stores the energy it harvests from its surroundings and operates utilizing only this energy. Moreover, ZEDs do not transmit data constantly, so their operation can be based on a duty cycled manner to conserve energy. That might also cause variations to the communication quality or to the energy harvested, due to objects temporarily blocking the transmission path [3].

Wireless powered networks (WPNs) are a networking paradigm in which the devices are charged by dedicated power transmitters, utilizing the WPT technology. Then, the devices can use the harvested energy for information transfer [4]. Studies on multiple access schemes for WPNs, so far, have focused on orthogonal multiple access (OMA) schemes such as time-division multiple access (TDMA), as in [5], or the emerging non-orthogonal multiple access (NOMA) protocol, as in [6]. However, the ZEDs' data requirements are expected to be low, while their computational capabilities are not suited for complex channel access methods [3]. Therefore, for WPNs with ZEDs, hereinafter named as zero-energy device networks (ZEDNs), contention-based protocols, which reduce the signaling overhead for coordination of the nodes and do not require global channel state information are a promising alternative. Among the available contention based protocols, slotted ALOHA (SA) is considered a prominent candidate for IoT applications. SA is based on probabilistic transmissions during separated time slots which is appropriate for the duty cycled operation of the ZEDs. Furthermore, compared to other RA schemes, for example ALOHA, it has a reduced number of collisions while keeping the computational complexity low. The proportional fairness metric was optimized in a SA network with WPT in [7] and it was shown to increase the system's throughput in comparison to a benchmark random access (RA) scheme. Note that the analysis in [7] is case specific and cannot be extended to other metrics, while the circuit power consumption was not taken into account. Additionally, SA was also examined with NOMA in [8] for use in the next generation IoT. Also, SA with WPT was studied in [9] for UAV-mounted BS, while in [10] the sum throughput was maximized for a SA network with WPT. Moreover, a WPN with SA is proposed in [11] which exploits idle data transmission slots for WPT.

Motivated by the above considerations, we propose a novel energy-aware resource allocation scheme for ZEDNs with SA. Specifically, the average energy consumption of all ZEDs, i.e., the energy harvested, in the SA network is minimized while ensuring that all ZEDs can satisfy their required QoS. The practical significance of this problem can be highlighted by the fact that WPT can offer a very limited amount of energy to ZEDs, so the design of novel energy efficient resource allocation schemes is of paramount importance, in order to fully exploit the capabilities of WPT and ZEDs. Therefore, in contrast to the existing literature on WPT with SA, the circuit power consumption has to be studied, since its value

Manuscript received December 13, 2021; revised January 17, 2022; accepted January 19, 2022. Date of publication February 4, 2022; date of current version April 11, 2022. This research has been co-financed by the European Regional Development Fund by the European Union and Greek National Funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call: "Special Actions: Aquaculture—Industrial Materials—Open Innovation in Culture (project code: T6YBP-00134). The associate editor coordinating the review of this letter and approving it for publication was L. Mohjazi. *(Corresponding author: Vasilis K. Papanikolaou.)*

The authors are with the Wireless Communications and Information Processing (WCIP) Group, Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54636 Thessaloniki, Greece (e-mail: nmitsiou@ece.auth.gr; vpapanikk@auth.gr; padiaman@ieee.org; geokarag@auth.gr).

Digital Object Identifier 10.1109/LCOMM.2022.3149142

is comparable to the transmit power of ZEDs [3] and it is expected to essentially impact their performance. To this end, we jointly optimize the WPT duration, the transmission probability and the transmit power of all ZEDs. The formulated optimization problem is non-convex and therefore it is difficult to be solved in a tractable manner. In order to find its global optimal solution, the original problem is transformed into an equivalent convex one and its optimal solution is derived in closed form, with respect to the Lagrange multipliers. Finally, simulation results verify that taking into account the circuit power consumption leads to a much more energy efficient resource allocation scheme, without QoS degradation, which is critical for the case of ZEDs.

II. System Model

We consider a ZEDN consisting of one BS, which also acts as a power beacon, and K ZEDs with a single antenna and a shared frequency band. The total communication time is separated into time slots of length T. Each time slot is divided into two distinct phases, one phase of energy harvesting and one phase of data transmission. The duration of the first phase is denoted as $(1-\tau_0)T$, where τ_0 is a time-sharing parameter $(0 \leq \tau_0 \leq 1)$.

The rechargeable mechanism of every ZED is modeled as an energy queue with an infinite storage capacity [7]. We denote the average amount of power that arrives at the energy queue as $P_{\mathrm{har},k}$. For notation simplicity and without loss of generality, $P_{\mathrm{har},k}$ contains both the power that is harvested and can be calculated by using any harvest model, linear [7] or non linear [12], and the power losses that occur during the ZED's operation at the harvest phase. The energy harvested from interference is negligible, since the devices' transmit power is much smaller than the transmit power of the BS in practice. Thus, the average energy arrival rate at the k-th device, is given by

$$E_{\mathrm{har},k} = T\left(1-\tau_0\right)P_{\mathrm{har},k}. \tag{1}$$

In the remaining time, $\tau_0 T$, of the second phase, a SA communication protocol is adopted. The transmission probability, i.e., the probability with which a ZED will transmit data at the beginning of the transmission phase, and the transmit power of the k-th ZED are denoted as q_k and P_k respectively. However, in addition to the transmit power, each device also consumes a constant circuit power, $P_{c,k}$, accounting for the power needed to operate its transmit filter, mixer, frequency synthesizers, etc., which eventually reduces the overall maximum power that can be used for data transmission. Then, the average energy departure rate from the energy queue, is

$$E_{\mathrm{con},k} = T\tau_0\left(P_k + P_{c,k}\right)q_k. \tag{2}$$

The uplink communication channel between the ZEDs and the BS, is considered to be quasi-static and its instantaneous values follow a Rayleigh distribution. With this assumption, the average throughput of the k-th ZED is given by [7] as

$$\bar{R}_k = T\tau_0 R_k \exp\left(-\frac{(2^{R_k}-1)N_0}{L_k P_k}\right) q_k \prod_{i\neq k}\left(1-q_i\right), \tag{3}$$

where $\tau_0 R_k$ (bps/Hz) is the fixed transmission rate of the k-th ZED, N_0 is the spectral density of additive white Gaussian noise (AWGN) and L_k is the path loss between the k-th ZED and the BS. For convenience, we set $L_k = 1$.

III. Optimal Resource Allocation for Energy Minimization

A. Formulation of the Problem

The aim of the proposed analysis is to minimize the average energy consumption of the ZEDs, while satisfying their QoS requirements. In our system model, this is equivalent to minimizing the average harvested energy, since the ZEDs operate using only WPT. It should also be noted that WPT can provide a limited amount of energy to ZEDs, so the design of energy-efficient schemes is necessary.

Furthermore, the formulated optimization problem considers the resource allocation for one time slot. However, the optimization problem is not required to be solved on a slot-per-slot basis. We study the average throughput of the ZEDs, so regarding the small scale fading of the system, the BS only assumes as known the statistic properties of the channel. The only parameter necessary for the problem to be solved is the large scale fading. Considering the low, if any, mobility of the ZEDs, its effect can assumed fixed for a duration larger than several time slots. Moreover, due to the use of SA in the uplink, there is a reduced need for coordination between the ZEDs. Consequently, the communication overhead is negligible. Also, $P_{\mathrm{har},k}$ can be assumed known as well. For notation simplicity we will assume that $T = 1$. To this end, we formulate the following energy minimization problem

$$\begin{aligned}
&\min_{\boldsymbol{\tau_0},\mathbf{R},\mathbf{P},\mathbf{q}} \sum_{k=1}^{K} P_{\mathrm{har},k}\left(1-\tau_0\right)\\
&\text{s.t } \mathrm{C}_1: \ \bar{R}_k \geq R_{th,k},\\
&\quad\ \ \mathrm{C}_2: \ \tau_0\left(P_k + P_{c,k}\right)q_k \leq \left(1-\tau_0\right)P_{\mathrm{har},k},\\
&\quad\ \ \mathrm{C}_3: \ 0 \leq \tau_0 \leq 1, \quad 0 \leq q_k \leq 1.
\end{aligned} \tag{4}$$

As seen from (4), the proposed problem can equivalently be modeled as maximizing the data transmission time of the second phase. The constraint C_1 guarantees that the average data rate of all devices is at least equal to their QoS requirements. Also, the duty cycled operation of the ZEDs might cause variations in the energy harvested [3], therefore the energy harvested during previous time slots might be utilized in the transmission phase of future time slots. Consequently, to guarantee that the energy queue is stable, the average energy departure rate has to be no greater than the average energy arrival rate, which is ensured with constraint C_2. The problem is non-convex, due to both constraints C_1,C_2 containing products of at least two variables of the problem. To overcome this, the logarithm of both sides of the inequalities is taken and the problem is rewritten as

$$\begin{aligned}
&\max_{\boldsymbol{\tau_0},\mathbf{R},\mathbf{P},\mathbf{q}} \ \tau_0\\
&\text{s.t } \mathrm{C}_1: \ \log\left(R_k\tau_0\right) - \frac{(2^{R_k}-1)N_0}{P_k} + \log\left(q_k\right)
\end{aligned}$$

$$
\begin{aligned}
&+\sum_{i\neq k}\log\left(1-q_i\right)\geq \log R_{th,k},\\
&\mathrm{C}_2: \ \log\left(\tau_0\right)+\log\left(P_k+P_{c,k}\right)+\log\left(q_k\right)\\
&\quad -\log\left(\left(1-\tau_0\right)P_{\mathrm{har},k}\right)\leq 0,\\
&\mathrm{C}_3: \ 0\leq\tau_0\leq 1, \quad 0\leq q_k\leq 1, \qquad (5)
\end{aligned}
$$

The problem is still non-convex due to the second term of constraints C_1 and C_2. In practice, a ZED will always have to transmit data in order to satisfy its QoS threshold. Otherwise, the initial problem is infeasible. We deduce, then, that the variables of the problem are positive and the following auxiliary variables can be introduced

$$
2^{R_i}-1=\exp(\tilde{R}_i), \quad \exp(\tilde{P}_k)=P_k, \quad \exp(\tilde{\tau}_0)=\tau_0, \quad \exp(\tilde{q}_k)=q_k. \qquad (6)
$$

Taking into account that $\exp(x)$ is a monotonically increasing function, we end up with the following convex formulation

$$
\begin{aligned}
&\max_{\boldsymbol{\tau}_0,\mathbf{R},\mathbf{P},\mathbf{q}} \quad \tilde{\tau}_0\\
&\text{s.t } \mathrm{C}_1: -\tilde{\tau}_0-\log\left(\log_2\left(\exp(\tilde{R}_k)+1\right)\right)+N_0\exp\left(\tilde{R}_k-\tilde{P}_k\right)\\
&\quad -\tilde{q}_k-\sum_{i\neq k}\log\left(1-\exp\left(\tilde{q}_i\right)\right)+\log R_{th,k}\leq 0,\\
&\mathrm{C}_2: \tilde{\tau}_0+\log\left(\exp(\tilde{P}_k)+P_{c,k}\right)+\tilde{q}_k-\log\left(P_{\mathrm{har},k}\right)\\
&\quad -\log\left(1-\exp(\tilde{\tau}_0)\right)\leq 0,\\
&\mathrm{C}_3: \tilde{\tau}_0\leq 0, \quad \tilde{q}_k\leq 0. \qquad (7)
\end{aligned}
$$

It can easily be shown that the eigenvalues of the Hessian of the term $\exp\left(\tilde{R}_k-\tilde{P}_k\right)$ in C_1 are non negative. Also, in both C_1 and C_2, the second derivatives of the positive log-exp terms are non-negative, while the second derivatives of the negative log-exp terms are non-positive. The rest of the terms are linear and therefore problem (7) is convex. The global optimal solution of the problem can now be obtained by using standard numerical methods such as the interior point or the Lagrange Dual decomposition (LDD) [13]. The latter proves to be a more beneficial choice since, via the Lagrange multipliers (LMs), closed form expressions for all the variables can be obtained.

B. Solution of the Problem

To this end, the problem is divided into two consecutive layers, Layer 1 and Layer 2. In Layer 1, for given values of the LMs, the Karush Kuhn Tucker (KKT) conditions are exploited to find the optimal set of variables that solve problem (7). In Layer 2, using the subgradient method, the LMs can be updated in a parallel manner. Both layers are solved iteratively and for a convex problem, the algorithm converges to the optimal point in a reasonable number of steps.

Layer 1: The Lagrangian dual function, $\mathcal{L}$, of the primal problem (7) is given as,

$$
\begin{aligned}
\mathcal{L}=&-\tilde{\tau}_0+\sum_{k=1}^{K}\lambda_{1,k}\Big(-\tilde{\tau}_0-\log\left(\log_2\left(\exp(\tilde{R}_k)+1\right)\right)-\tilde{q}_k\\
&+N_0\exp\left(\tilde{R}_k-\tilde{P}_k\right)-\sum_{i\neq k}\log\left(1-\exp\left(\tilde{q}_i\right)\right)+\log R_{th,k}\Big)\\
&+\sum_{k=1}^{K}\lambda_{2,k}\Big(\tilde{\tau}_0+\log\left(\exp(\tilde{P}_k)+P_{c,k}\right)+\tilde{q}_k-\log\left(P_{\mathrm{har},k}\right)\\
&-\log\left(1-\exp(\tilde{\tau}_0)\right)\Big). \qquad (8)
\end{aligned}
$$

where $\lambda_{1,k}, \lambda_{2,k}\geq 0$ are the Lagrange multipliers related to C_1 and C_2 for the k-th user respectively. Applying the KKT conditions leads to,

$$
\frac{\partial\mathcal{L}}{\partial\tilde{P}_k^*}=0, \quad \frac{\partial\mathcal{L}}{\partial\tilde{q}_k^*}=0, \quad \frac{\partial\mathcal{L}}{\partial\tilde{R}_k^*}=0, \quad \frac{\partial\mathcal{L}}{\partial\tilde{\tau}_0^*}=0 \qquad (9)
$$

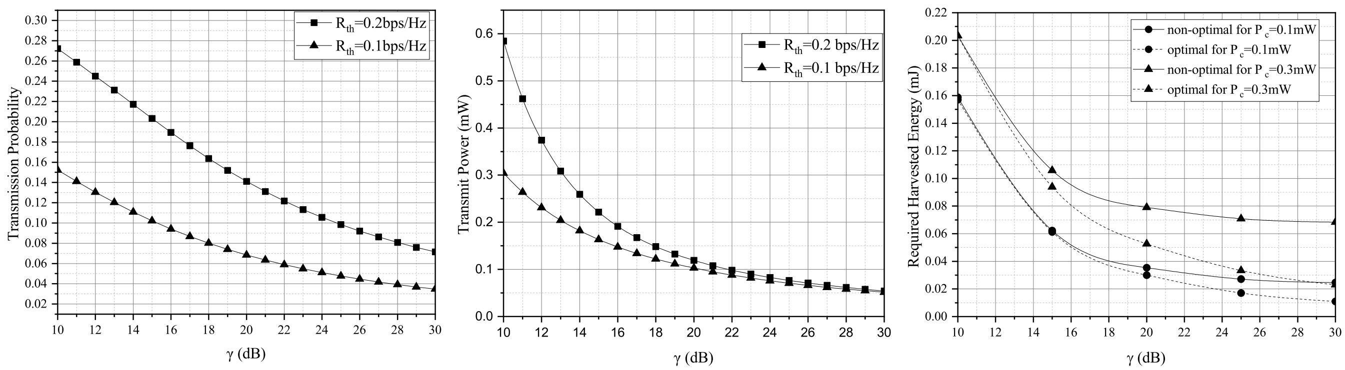
and after some algebraic manipulations the optimal values of the energy minimization problem can be calculated by the following set of closed form equations,

$$
\tilde{P}_k^*=\log\left(\frac{\lambda_{2,k}}{\lambda_{1,k}}-P_{c,k}\right), \qquad (10)
$$

$$
\tilde{q}_k^*=\log\left(\frac{\lambda_{1,k}-\lambda_{2,k}}{\sum_{i=1}^{K}\lambda_{1,i}}\right), \qquad (11)
$$

$$
\tilde{R}_k^*=\log\left(\exp\left(W\left(\frac{\exp\left(\tilde{P}_k^*\right)}{N_0}\right)\right)-1\right), \qquad (12)
$$

where $W(x)$ denotes the Lambert W function, also called the omega function or product logarithm, which gives the principal solution for $W(x)$ in $x=W(x)e^{W(x)}$. From (10) and (11) we conclude that $\lambda_{1,k}>0$ and $\lambda_{2,k}>0$, so the optimal value τ_0^* can be found from either the constraint C_1 or the constraint C_2 holding with equality. At this point, it should be noted that the solution of the initial problem (4) can be found by combining the inverse transformation of (6) and relations (10)–(12). Regarding the coordination overhead of the proposed model, from (10)–(12), it can be concluded that only the values of the optimal transmit power and the transmission probability have to be provided to the ZEDs. Therefore, a total of $2K$ variables are shared, K being the number of ZEDs. This allocation, due to the slowly varying large-scale fading, will be taking place rarely, once in many time slots. On the other hand, for a scheduling which depends on collision avoidance the overhead increases, since a total of $3K$ variables have to been transferred from the BS to the ZEDs. Specifically, the value of the optimal transmit power, the time duration that each ZED can utilize to offload its data and the exact moment in time in which a ZED will begin to transmit data have to been transmitted to all ZEDs, without considering the required synchronization overhead among the ZEDs. Also, it should be noted that the formulated energy efficient SA protocol can be used as a benchmark for comparison with simpler RA schemes. For example, a RA scheme may provide less overhead, which is important for ZEDs, at the expense of energy efficiency. Moreover, the proposed mathematical analysis is valid and can be used for an OMA protocol, as well, when the coordination is solely based on the channels statistics. It is noted that this problem has not been considered before in the existing literature. Finally, by removing the term $\prod_{i\neq k}\left(1-q_i\right)$ in (3) and by slightly adjusting the rest of the relations accordingly, the analysis can be modified to meet the particularities of an OMA scheme.



(a) The optimal transmission probability when $P_c = 0.1$mW

(b) The optimal transmit power

(c) The average required harvested energy

Fig. 1. The optimal resource allocation strategy vs γ.

Layer 2: The dual function is differentiable, therefore the subgradient method can be used, as shown

$$\lambda_{1,k}^{(t+1)} = \Big[\lambda_{1,k}(t)+\alpha_1(t)\Big(\tilde{\tau}_0^*+\tilde{q}_k^*-N_0\exp\left(\tilde{R}_k^*-\tilde{P}_k^*\right)\log R_{th,k} + \sum_{i\neq k}\log\left(1-\exp\left(\tilde{q}_i^*\right)\right)+\log\left(\log_2\left(\exp(\tilde{R}_k^*)+1\right)\right)\Big)\Big]^+ \tag{13}$$

$$\lambda_{2,k}^{(t+1)} = \Big[\lambda_{2,k}(t)+\alpha_2(t)\Big(\log\left(P_{\text{har},k}\right)-\tilde{q}_k^*-\tilde{\tau}_0^* - \log\left(\exp(\tilde{P}_k^*)+P_{c,k}\right)+\log\left(1-\exp(\tilde{\tau}_0^*)\right)\Big)\Big]^+, \tag{14}$$

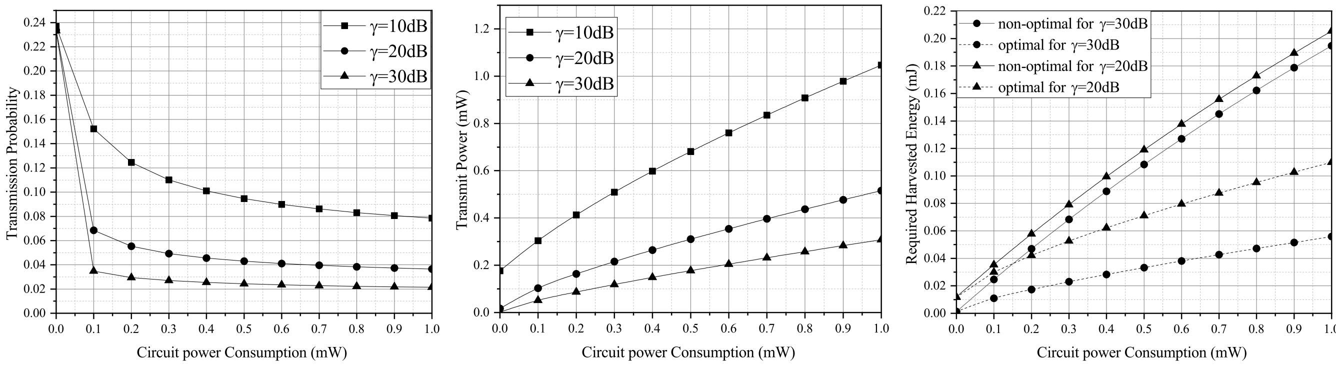
where $[\cdot]^+ = \max(\cdot, 0)$. Index t is the recursion index and $a_j^{(t)}$, $j \in \{1, 2\}$, are positive step sizes, chosen in order to satisfy the diminishing step size rules [13]. It is interesting to note that by exploiting the proposed iterative method, the problem can be decomposed in K subproblems which can be solved in parallel by a central unit. This can be utilized from the BS to solve efficiently the problem without increasing the complexity of the end users, which is particularly important for ZEDs.

IV. Numerical Results and Discussion

In this section, we present simulation results of a two ZEDs network, which without loss of generality, have equal amounts of average harvested power, $P_{\text{har},k} = P_{\text{har}} = 1$mW, $k \in \{1, 2\}$. Also, their circuit power consumption, $P_{c,k} = P_c$, is equal during data transmission. The path loss L_k between the ZEDs and the BS is included into $\gamma_k = \frac{L_k}{N_0}$ which is an expression that measures the quality of the communication channel and should not be confused with the conventional signal-to-noise-ratio (SNR). Now on, γ denotes the mean value of all γ_k. Greater values of γ indicate a more beneficial communication channel in the uplink between the ZEDs and the BS, either due to a lower signal attenuation or due to a less noisy channel or both. The resource allocation presented in the figures of this section concern the performance of the first user, however very similar allocation holds for the second user, so the results can be generalized for both ZEDs.

In Fig. 1, the optimal transmission probability, the transmit power and the energy consumption are plotted for various combinations of P_c, R_{th} and γ. From Fig. 1b, it is shown that for better channel conditions, the optimal transmit power of each ZED declines. Also, in Fig. 1a, the optimal transmission probability is shown to decline as well. One might guess that for better channel conditions, less time should be dedicated to the data transmission phase in order for the ZEDs to satisfy their QoS. However, by taking into account Fig. 1a-1b and (3), we can conclude that for better channel conditions a larger time duration is assigned to the transmission phase instead. Therefore, the time dedicated to the energy harvesting decreases and, from (1), the average harvested energy decreases as well. Since the ZEDs operate by utilizing only the energy harvested from WPT, the resource allocation of Fig 1a-1b lead to an energy efficient system.

As mentioned, in Fig. 1a, for increased values of γ, the optimal value of the transmission probability reduces. In contradiction, from Fig. 2a, a system which ignores the circuit power consumption, i.e for $P_c = 0$, retains the same transmission probability for all channels conditions. Interestingly, this subtle difference in the resource allocation has a great impact in the energy consumption of the ZEDs, as it is evident from Fig. 1c. In Fig. 1c, the optimal system is compared with a non-optimal system, which does not account for the circuit power consumption. Specifically, the transmission probability of the non-optimal system is chosen equal to the optimal transmission probability when $P_c = 0$ and the rest of the variables are optimized for every γ. In the case of $P_c = 0.1$mW the optimal system can be seen to achieve 6dB better performance than the non-optimal system. That practically means that the optimal system achieves an equal QoS with the non-optimal system while harvesting an equal amount of energy, but for channel conditions worse by 6dB. For $P_c = 0.3$mW the optimal system outperforms the non-optimal system for more than 10dB. This is explained by the fact that the optimal system uses a smaller transmission probability and since the circuit consumes power



(a) The optimal transmission probability (b) The optimal transmit power (c) The average required harvested energy

Fig. 2. The optimal resource allocation strategy vs the circuit power consumption.

during the transmission phase, rarer transmissions lead to less averaged consumed power. Also, the performance gap grows for bigger values of γ or P_c.

In Figs. 2a-2c the effect of circuit power consumption is studied in detail. In Fig. 2a the optimal transmission probability is plotted for different values of P_c. It is observed that its value decreases for increased values of P_c. This is attributed to the circuit consuming power during the data transmission phase, therefore infrequent data transmission attempts result in energy savings. In consequence, the energy saved can be exploited during the data transmission phase, for a smaller outage probability to be provided. This can be verified in Fig 2b, where the transmit power is shown to increase in conjunction with the circuit power consumption.

In Fig. 2c, the comparison between the optimal and the non-optimal system is plotted for various values of the circuit power consumption P_c. The non-optimal system is the one used in Fig. 1c. For $\gamma = 20$dB we observe that the optimal system, in comparison to the non-optimal system, needs to harvest about 50% less energy, while for the case of $\gamma = 30$dB it needs to harvest about 66% less energy. Therefore it is much more efficient than the non-optimal system. It should be noted that the performance gap grows for better channel conditions, or in the case where the circuit power consumption is comparable to the average harvested power. From Fig. 1c and Fig. 2c we can conclude then, that taking into account the circuit power consumption is crucial in a ZEDN, since it leads to a much more energy efficient resource allocation scheme.

V. Conclusion

In this study, we proposed a novel resource allocation scheme, which aims to minimize the energy consumption of ZEDs. Their available energy is extremely limited, since they operate utilizing only the energy harvested from a dedicated power beacon. Therefore, the circuit power consumption had also to be taken into account since its value is comparable to the ZEDs transmit power. The formulated energy minimization problem was non-convex, so it was transformed to an equivalent convex one, in order for its optimal solution to be derived. The proposed energy efficient scheme can be used as a benchmark for simpler RA schemes, while the mathematical analysis is valid and can be used for an OMA protocol as well, when the coordination is solely based on the channels statistics. Finally, numerical results were presented, that verify the non-trivial impact of taking into account the circuit consumption. Our optimal design was found to be more efficient that the respected non-optimal design which ignores the circuit power consumption, with no QoS degradation.

References

[1] J. Koomey, S. Berard, M. Sanchez, and H. Wong, "Implications of historical trends in the electrical efficiency of computing," *IEEE Ann. Hist. Comput.*, vol. 33, no. 3, pp. 46–54, Mar. 2011.

[2] T. D. P. Perera, D. N. K. Jayakody, S. K. Sharma, S. Chatzinotas, and J. Li, "Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 264–302, 1st Quart., 2018.

[3] (Sep. 2021). *Zero-Energy Devices-A New Opportunity in 6G*. [Online]. Available: https://www.ericsson.com/en/blog/2021/9/zero-energy-devices-opportunity-6g

[4] S. Bi, Y. Zeng, and R. Zhang, "Wireless powered communication networks: An overview," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 10–18, Apr. 2016.

[5] X. Kang, C. K. Ho, and S. Sun, "Optimal time allocation for dynamic-TDMA-based wireless powered communication networks," in *Proc. IEEE Global Commun. Conf.*, Austin, TX, USA, Dec. 2014, pp. 3157–3161.

[6] P. D. Diamantoulakis and G. K. Karagiannidis, "Maximizing proportional fairness in wireless powered communications," *IEEE Wireless Commun. Lett.*, vol. 6, no. 2, pp. 202–205, Apr. 2017.

[7] Z. Hadzi-Velkov, S. Pejoski, N. Zlatanov, and R. Schober, "Proportional fairness in ALOHA networks with RF energy harvesting," *IEEE Wireless Commun. Lett.*, vol. 8, no. 1, pp. 277–280, Feb. 2019.

[8] S. A. Tegos, P. D. Diamantoulakis, A. S. Lioumpas, P. G. Sarigiannidis, and G. K. Karagiannidis, "Slotted ALOHA with NOMA for the next generation IoT," *IEEE Trans. Commun.*, vol. 68, no. 10, pp. 6289–6301, Oct. 2020.

[9] Z. Hadzi-Velkov, S. Pejoski, R. Schober, and N. Zlatanov, "Wireless powered ALOHA networks with UAV-mounted-base stations," *IEEE Wireless Commun. Lett.*, vol. 9, no. 1, pp. 56–60, Jan. 2020.

[10] M. Moradian and F. Ashtiani, "Sum throughput maximization in a slotted Aloha network with energy harvesting nodes," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Istanbul, Turkey, Apr. 2014, pp. 1585–1590.

[11] H.-H. Choi, W. Shin, M. Levorato, and H. V. Poor, "Harvest-or-access: Slotted ALOHA for wireless powered communication networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 11, pp. 11394–11398, Nov. 2019.

[12] S. A. Tegos, G. K. Karagiannidis, P. D. Diamantoulakis, and N. D. Chatzidiamantis, "New results for Pearson type III family of distributions and application in wireless power transfer," 2020, *arXiv:2011.01332*.

[13] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.